Identifying urban boundaries: application of remote sensing and geographic information system technologies¹

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Abstract: This paper focuses on a new definition of urbanization trends by investigating the concept of a fuzzy urban boundary (UB) that assigns different membership levels to urbanized aggregates based on a proposed composite index. The research work builds on this logic to investigate a new approach in defining urbanized areas by compounding the characteristics of the fuzzy density of an urban agglomeration with land use variation and intensity of economic activity. Spatial overlaying capabilities of geographic information system (GIS) are used to model the urbanization trend in the case study of Greater Beirut. The UB is defined using a multispectral high resolution visible (HRV) Satellite Pour L'observation de la Terre (SPOT) satellite image. The challenges of urban modelling using satellite images are addressed through an investigative approach in cartographic feature extraction and delineation of the urban agglomeration. This entails image treatment of the spot HRV image, defining internal characteristics of the urban agglomeration and constructing spatially continuous socio-economic data sets that can be combined with the digital remotely sensed image.

Key words: fuzzy logic, GIS, remote sensing, spatial urban modelling, urban boundary, urbanization trends.

Résumé : Cet article porte sur une nouvelle définition des tendances en urbanisation en étudiant le concept d'une frontière urbaine floue qui assigne différents niveaux d'appartenance aux agglomérations urbaines selon un index composite proposé. Le travail de recherche part de cette logique pour étudier une nouvelle approche de définition des zones urbanisées en compilant les caractéristiques de la densité floue d'une agglomération urbaine avec des variations de l'utilisation du sol et l'intensité de l'activité économique. Les capacités de superposition spatiale du SIG sont utilisées pour modéliser la tendance d'urbanisation dans l'étude de cas du grand Beyrouth. La frontière urbaine est définie en utilisant une image Spot satellite multispectrale visible haute résolution (VHR). Les défis posés par la modélisation urbaine utilisant les images-satellite sont abordés en utilisant une approche par enquête dans l'extraction et la délimitation des caractéristiques cartographiques de l'agglomération urbaine. Cela donne lieu à un traitement d'image de l'image Spot VHR, définissant les caractéristiques internes de l'agglomération urbaine et construisant des ensembles de données socioéconomiques spatialement continus qui peuvent être combinés à une image de télédétection digitale.

Mots clés : logique floue, SIG, télédétection, modélisation spatiale urbaine, frontière urbaine, tendances en urbanisation.

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1. Defining urbanization

The world has reached a time where nearly half its population is living in urban areas. Within a generation, and for the first time in human history, the urban population will surpass the rural population. The population of the developing world will be mainly urban. Small cities will continue to dominate but larger ones will be gaining in share of urban population (United Nations 1995a). Africa and the Middle East have been witnessing one of the highest increases of urbanization since 1970. These trends put further pressures on cities to resolve urban poverty, enhance public health, safety

and security, and address "brown" environmental problems and urban congestion that have direct impacts on household welfare and on productivity.

While these pressures have been increasingly present since the early modernization stages of cities in the developing world, two important factors contribute to new directions that shift our understanding of the dynamics of urbanization and its problems. First, and contrary to the general belief in its "evils", urbanization over the past 25 years has been a major agent in the overall improvement of incomes and quality of life experienced by the developing countries (Cohen 1999). Economic studies have shown that cities increas-

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ingly account for the lion's share of gross national product and wealth creation. Second, the monocentric age-old model of the city and its suburbs is no longer sufficient to explain the complexities in the operation of an urban agglomeration. Instigated by financial deregulation and spawned by increasing levels of international and national market competitions, changes to the modes of production, accumulations, and economic relations have induced a restructuring of the division of labour on a global scale. This economic restructuring is causing major sectoral changes mirroring a marked decline in manufacturing employment, a sharp rise in service-related industries and with it a change in the commuting and settlement patterns of the labour force (Friedman 1992; Held 1990; Toffler 1990; Yiftachel and Alexander 1995). Furthermore, a higher level of mobility induces the current process of decentralization of economic activity to the periphery with a marked increase in the distance between the dwelling and the workplace (Massot and Orfeuill 1995). The multicentrism that characterized cities many decades earlier is evolving through further fragmentation and widespread sprawl. This trend greatly impacts physical changes to the richness in land use patterns around the conventional city "boundaries" as well as changes and variations to percentages of active residents whether in the centre, first, second, old, or more recent periurban regions of the city. In this respect, limiting our study of urbanization patterns to the level of concentration of population is no longer valid.

The complexity in defining the spatial boundaries of the modern city has even pushed a few thinkers to negate its presence. James Donald in his *Metropolis: The City as Text* clearly illustrates this phenomenon by writing: "To put it polemically, there is no such thing as a city. Rather the city designates the space produced by the **interaction** [our emphasis] of historically and geographically specific institutions, social relations of production and reproduction, practices of government, forms and media of communication, and so forth..." (Donald 1992)

The emerging nature of the problems in such agglomerations begs a larger framework. To manage externalities, both positive and negative, this framework needs to encompass the urban agglomeration and its peripheries within one single metropolis going beyond the historical administrative limits of the city. How we define the limits of such metropolis hinges on our definition of these urbanized agglomerations and their boundaries.

This paper contributes to the making of urban models through the integration of both remote sensing and GIS technology that enable to capture, manipulate, analyze, recognize patterns, and display all forms of geographically referenced information. These technologies are capable of revealing in a global and exhaustive manner the geographically tied problem.

2. Theoretical framework in modelling urbanization

2.1. Approach

Within the field of quantitative planning, modelling of the city attempts to capture the complexity of the interplay among relations of production, consumption, and exchange. The definitions that are emerging are most often set within

formulae quantifying the interactive forces that shape urbanization in a continuous and dynamic manner. This trend is in fact shifting modelling of urbanization patterns to relational typologies. The relational approach provides indicators that highlight changes among the geographic, demographic, and socio-economic variables that characterize the internal attributes of the urban settlement.

2.2. Role of fuzzy logic

Urbanization is characterized by being specific to its context, carries a spatial continuum, varies in an ambiguous and uncertain manner, and is shaped by complex layering of an urban geographic space (social, political, and economic). In this respect, urbanization resists the arbitrariness of applying abstract canonical measures that lead to its demarcation by a one-dimensional line separating it from "nonurbanized" areas. Within this context the Boolean logic would not be appropriate to measure processes that are based on the behaviour of (spatially interacting) objects and (or) spatial entities, the resulting pattern of which can be expressed by the spatial distribution and the state of these objects (urbanized areas, in our case). Measuring the membership level to urbanization would bring us closer to the representation of the complex urban pattern on the ground. Fuzzy logic is proposed as an appropriate framework for a formal representation and analysis of uncertain database, structure, and process as it is more amenable to policy analysis and planning with inexact information and value based standards. The merit of the application of fuzzy sets approach in behavioural geography, cartography, remote sensing, and soft spatial data analysis has been thoroughly recorded (Leung 1983).

2.3. Remote sensing and geographical information system applications

The rapid urbanization of the 1970s instigated a lot of research and conferences investigating its problematic and consequence on urban growth (Cullingworth 1973, 1977; Alam and Alikhan 1994). The direction of the researches in this field, however, has historically witnessed many turns that depended heavily on the available technology. The attempt to rationalize planning in the 70s, for instance, meant an explanation of urban phenomena through mathematical large-scale comprehensive models (Bernstein and Mellon 1978; Putman 1983; Bertuglia et al. 1994). Despite many pitfalls that it was subjected to, the "art" of urban modelling has been informed by a proliferation of theoretical advancement in classical and modern theories of location (Losch 1956), physical analogy (Stewart 1948), and economic sociology. While the latter attempted to explain location and movement of population and industry in terms of economic and social factors (Lowry 1964), model development adopted the use of systems of linear equations with coefficients determined by the use of econometric methods (Pindyck and Rubinfeld 1991).

The contemporary research works of Anys et al. (1994) and Bannari et al. (1994) are of direct relevance to this paper. The major denominator that characterizes their work is the investigation of the potentials and the attempt to surmount the constraints found in remote sensing technology, more specifically in image enhancement, image classification, and change detection.

An important factor, dealt with within the paper, which degrades current remote sensing image analysis, lies in the loss of spectral information during the process of image classification. The information loss is caused by the expressive inadequacy of the traditional method for representing geographical information and its dependency on spectral statistical analysis. This traditional method is based on classical set theory that is ideally suitable for objects that can be precisely prescribed by full membership in a set. To improve remote sensing image analysis, an alternative representation method is required that allows for partial and multiple membership.

Accordingly, the investigation resorted to the application of the fuzzy set theory and the use of the fuzzy set classifier. The fuzzy representation may reduce the information loss and arrive at a higher overall classification accuracy and identification of types and proportions of component cover classes in mixed pixels. It has recently received considerable attention from the remote sensing community. Recognizing that traditional classifiers based on rigid, discrete classes contribute to noticeable thematic inaccuracy, the notion that a pixel can enjoy partial membership in a given informational class is an attractive alternative to the two-value logic implicit in most classification procedures. A fuzzy classification technique utilizing the fuzzy c-means (FCM) algorithm was adopted. The standard FCM objective function for partitioning pixels into c clusters of approximately the same size is given by Bezdek and Pal (1991). The FCM objective function is minimized when high membership values are assigned to pixels whose intensities are close to the centroid of its particular class, and low membership values are assigned when the pixel data are far from the centroid.

3. Model components in defining intensity of urbanization

The proposed “intensity of urbanization” model is constructed upon three variables: (i) density of the built-up area, (ii) relative richness of land use, and (iii) intensity of economic activities in the various statistical units

These three components define in a comparative and dynamic way the intensity of urbanization. The process is presented in the cartographic model depicted in Fig. 1.

The above-mentioned parameters were informed by the theoretical effort of the Chicago School that to our mind still offers a model of urban organization applicable to urban agglomerations in the developing countries. The layers of the model follow the broad ecological processes defined by McKenzie (Park et al. 1925): concentration, centralization, and diversification. Such processes naturally lend themselves to rationalization through a relational typology (vs. adopting an a priori “yard-stick” measure that works within a Boolean logic and that abstracts in a reductive manner the complex interactive layering and contextual-based characterization of the urbanization process).³ These processes manifest themselves in three possible interrelated factors, namely, concentration of productive sector (industrial and tertiary sector),

concentration of population and density of social relations deriving from the heterogeneous and complementary nature of social groups, and diversity in functions.

It would be argued that the three layers of the model form one possible spatial materialization of these processes and expose the spatial structure of the urbanization process. This argument is reinforced by location theory (Murata 1959), localization and urbanization economies of scale (Hanink 1997), and the theory of the articulation of the economic system in space (Castells 1996).

As has been mentioned before, the logic of using a satellite image is based on the capacity of remote sensing to capture data of the area under study in a holistic manner. With the absence of alternative data sources, the use of high-resolution satellite images has been proven very effective in providing the necessary database for the analysis of the problem at hand. Typical treatment of satellite images and subsequent feature extraction are discussed in detail in the case study.

Density of development cannot reflect separately the density of urbanization, especially with the trend of the suburban “dormitories” that have emerged in the last decades. To avoid the pitfall of urban density alone, the relative richness of land use becomes an important agent in characterizing urbanization. The intensity of economic activity of a statistical zone (sz) is calculated on the basis of existing number of employees with respect to number of built units in that sz and with respect to its area. Rather than choosing the area of the sz alone, this alternative is adopted to eliminate the distortion in the model of urbanization in case of the presence of parks, forests, or any other open or high sloping area in the sz that may otherwise overstate the developable area. The number of employees is used rather than the number of commercial and industrial establishments because the latter does not distinguish between sizes of these establishments and hence the volume of economic turnover.

Finally the intensity of urbanization is measured by overlaying all three parameters in a model showing the fuzzy and continuous variation of intensity of urbanization over the geographic space. In following this approach, the model offers a new definition of urbanization trends by introducing the concept of a fuzzy logic. This approach assigns different membership levels to the urbanized aggregates based on their characterization according to the factors described above.

4. Case study of Beirut, Lebanon

4.1. A historical background

The reading of the urbanization development in Beirut has historically been framed by the interconnectedness of the city proper and its mushrooming periphery. In fact this notion of “Grand-Beyrouth” emerged at the end of the 1960s in the writings of the German geographer Helmut Ruppert in perpetuating a comparative analysis with the “two Berlins”. Nevertheless, this concept did not perpetuate the literature that addressed the urban growth phenomenon of Beirut. The notions of expansion of the city of Beirut beyond its munici-

³The United Nations has set up this a priori condition of urban agglomerations — a criterion that is based on the density of the built-up areas and that stipulates that “man-made area less than 200 metres distant from a unit already included in an urban morphological zone will be incorporated in this zone” (Morriconi-Ebrard 1994).

Fig. 1. Cartographic model in establishing intensity of urbanization.

pal boundaries continued to be mostly defined by Beirut and its suburb up until 1968, when Ecochard, the French town planner, acknowledged in his writings the presence of what he termed as Beirut and its suburb(s). The periurban environs of the city have become plural, denoting the heterogeneity of their nature. The urban agglomeration was then still possible to be perceived within the mono-centric conventional model of a centre and its periphery(ies) growing in a centripetal manner. In the context of the relative stability of the hostilities in 1983, the President of the Republic, Amine Jmail, declared in a political move the Greater Beirut or the Metropolitan Region of Beirut (MRB) as a zone that combines all competing factions in an armed-free zone monitored by the government. This region received a careful attention in terms of statistical surveys and studies that were manifested in the elaboration of a "Schema Directeur" done by the Franco-Lebanese Mission on Urbanism in 1986. Away from elaborating on the scheme itself, this study acknowledged the transformation of the urban agglomeration from this monocentric configuration to a multicentred urban development. This latter was shaped by the urbanization pattern in time but dramatically speeded up by the massive population displacements during the 16 years of civil strife (1975–1991).

The characteristics that have been the dominant agent in defining the metropolitan boundaries of Beirut were both geographic and political. These boundaries have been set by two river beds (the Al-Kalb River on the northern boundary and Al-Awalee River from the south), the sea from the west, and a topographical contour line that varied between 400 and 600 m from the east. The latter aspect was demarcated by political negotiations that reflected an ambiguity in the understanding of what areas should be included in the metropolitan boundaries. This arbitrary line of demarcation resulted in segmenting a few municipalities that are only partially included within the metropolitan boundary.

4.2. Density of urban agglomerations

To capture the continuous quality of the density and spatial distribution of the urban agglomeration of the city of Beirut and its periurban region, a set of SPOT-HRV images

was acquired with a raw level-1 image with ephemeris and attitude data recorded in the panchromatic mode (10 m pixel size) and multispectral mode (20 m pixel size). This set was captured on 24 January 1996. A 1991 one band SPIN-2 panchromatic image (2 m × 2 m resolution) and a set of 1998 1/5000 army maps helped in the identification of features and in registration of the SPOT satellite images. Specifically, the steps that were followed included (i) satellite image treatment to reduce atmospheric effect and correct topographic effect and (ii) feature extraction.

Satellite image treatment

Testing the satellite image has proven that the haze effect had to be removed. The haze effect was manifested through a relatively uniform elevation in spectral values in the visible bands. An effective method for reducing haze involved the application of principal component analysis (PCA). The PCA analysis was applied on the three bands (green, red, and infrared bands) resulting in components that are uncorrelated with each other and explain 95% to 99% of the variance in the original set of bands.

The topographic effect is defined simply as the difference in radiance values from inclined surfaces compared with horizontal ones. The interaction of the angle and azimuth of the rays of the sun with slopes and aspects produce topographic effects resulting in variable illumination. Given that the terrain surrounding the plateau of Municipal Beirut is mountainous, this necessitated the elimination of the topographic effect from the image. To do so there are different approaches, the most effective one in this case was the ratioing of the different bands of information. In band ratioing, one band image is divided by another, often a more robust normalized ratio, to limit the value range and avoid division by zero (United Nations 1995b)

$$[1] \quad \frac{\text{BandA} - \text{BandB}}{\text{BandA} + \text{BandB}}$$

Instead of using any of the infra-red or the red band, the first two images of the principal component analysis were used for this calculation. The resulting output image was

Fig. 2. Spot satellite image after treatment: reduction of atmospheric effect and topographic effects. The image on the right is a detail showing building–concrete cover in darker shades. Lighter shades indicate more reflection or the presence of a vegetation cover.

then linearly stretched back to the value range of 0 to 255 and used for image classification (Fig. 2).

Feature extraction

The principle of continuity of built-up area is defined by the potential use of the satellite image giving an average reflection value of a heterogeneous land cover within 20 m × 20 m (Fig. 3). The approach in feature extraction is based on relaxing the classification by moving away from the pixel-by-pixel identification. Rather than attempting to classify the value of a particular pixel by relating it to a surface and (or) cover type or class, our approach is to aggregate a set of pixel values in a training site where we know the percentage of that particular surface and (or) cover type. This approach presents a shift from the attempt to separate the mixture of surface cover classes in one pixel to group a mixture of pixels into one spectral class and (or) density. The decision that is conventionally framed as “How do I identify where a building is located?” (Where in this case, the building or more precisely the rooftop is the decision variable) is shifted to “How do I label the density of this development (high, medium, or low)?” At this point, the density is the decision variable.

Using the density of development as a fuzzy class, the candidate set of the decision will be the set of all locations (pixels) in the image that will be classified and categorized according to density of development. The following procedure by which criteria are selected and combined to arrive at a particular evaluation (which in our case is the definition of the fuzzy sets of urban densities) was adopted.

1. Define training sites from the 1/5000 army maps (43 random training sites were selected, 13 of which were used for accuracy assessment).
2. Calculate percentages of roof-top surfaces in relation to the overall surface of the training site itself.
3. Create a signature file for every training site.
4. Analyze the spectrum value of each training site and register its mean and standard deviation.

Fig. 3. Grid of 20 m × 20 m overlaid onto a 1/1000 map showing part of the urban agglomeration in the city of Beirut.

5. Record the relationship between the densities of built-up that is known a priori and the mean reflection value of this training site.
6. Assign a fuzzy membership grade indicating a continuous increase from nonmembership to complete membership of median reflection value for the fuzzy set of density of development.
7. Apply the sigmoidal membership curve for classification and select the pixels with zero membership to low-density class that is equivalent to densities of 35% and less. Full membership is assigned to densities of 45% and higher.

These steps produced the results shown in Fig. 4.

4.3. Relative richness of land use

Density of development cannot reflect separately the intensity of urbanization, especially with the trend of the suburban “dormitories” that have emerged in the last decades. To avoid the pitfall of urban density alone, the relative richness of land use becomes an important agent in characterizing urbanization.

To capture this richness, the most recent land use map (IAURIF 1985) has been utilized for this purpose. A kernel of 140 m × 140 m was adopted and the following equation was applied:

$$[2] \quad R = (n/n_{\max})100$$

where R is the relative richness of land use (Turner 1989), n is the number of different land use classes present in the kernel, and $n_{\max}$ is the maximum number of land use classes in the entire image.

The land use map contained 16 classes. Zones that are the richest in land use carried the highest value of R . Given the

Fig. 4. Delineation of the density of urban agglomerations through fuzzy logic.

Fig. 5. Relative richness of land use.

transformation of the raster land use map to a $20\text{ m} \times 20\text{ m}$ grid to be compatible with the spot satellite image, the highest value obtained was dependent on the size of the kernel ($7\text{ pixels} \times 7\text{ pixels}$). The value of R was found to take on

Fig. 6. Intensity of economic activity.

Fig. 7. Distribution of core-urbanized areas based on fuzzy logic.

six discrete values that were then labelled from 1 to 6. A buffer of 200 m was then created on the basis of the measure of walking distances from these zones to the surrounding areas. In calculating buffers around the various values of R ,

Fig. 8. Left, surface exploitation factor (SEF) in Greater Beirut; right, intensity of urbanization with the present metropolitan boundaries.

the highest value of relative richness was maintained. The results are shown in Fig. 5.

4.4. Intensity of economic activity

Adopting the 1996 surveys of the Central Administration of Statistics (CAS) meant an aggregation of data on the level of statistical zones (sz) that is based on cadastral subdivision and (or) boundaries and that, similar to the satellite image, comprised a region much larger than the metropolitan region of Beirut. The following steps were taken to calculate the intensity of economic activities.

1. Calculate the number of employees in the sz. As CAS provides the number of establishments in accordance with the number of employees categorized within six brackets (1–5, 6–10, ...), the number of employees is calculated by multiplying the mean number of employees of each category by the respective number of establishments.
2. Calculate the density of economic activity (D_{sz}) of sz based on the following equation

$$[3] \quad D_{sz} = E_{sz}/B_{sz}$$

where D_{sz} is the density of economic activity in the statistical zone, E_{sz} is the number of employees in the statistical zone, and B_{sz} is the number of built units in the statistical zone.

Next, the density of economic activity in the study area is normalized based on the surface area of the sz. Such normalization turns the density of economic activity into an intensity that is calculated according to the following equation:

$$[4] \quad I_{sz} = kD_{sz}$$

where I_{sz} is the intensity of economic activity of a statistical zone and k is a variable that brings into interplay the “spread” of the number of employees over the total area of

the statistical zone and is calculated according to the equation

$$[5] \quad k = E_{sz}/A_{sz}$$

where A_{sz} is the total area of the statistical zone.

The factor k is needed because the value of D_{sz} is based solely on the built area. This means that if a statistical zone has a restricted development along a central artery and the rest of the sz is geared towards agriculture or simply carries high slopes, for example, the E_{sz} may be high, providing a false reading of the intensity of economic activity of this sz.

To develop a comparative basis for this layer, the intensity of the economic activity of the statistical zone is normalized based on the I_{MB} of Municipal Beirut (Fig. 6). In this respect, the value of the normalized intensity of economic activity of the statistical zone (I_{sz}) will vary between 0 and 1 (1 being the highest value that is present in Municipal Beirut).

4.5. Intensity of urbanization

Finally, the model of intensity of urbanization that enables mapping the spatial extent of core urbanized zones is the compounding effect of the three layers developed so far, namely

$$[6] \quad IU = I_{sz} D_f R$$

where IU is the intensity of urbanization and D_f is the density of development with a fuzzy membership value between 0 and 1.

The result of the application of this model to the case study area is provided in Fig. 7 that shows the intensity of urbanization with the subsequent indication of the core-urban areas.

4.6. Insights

Two important issues emerged in comparing the modeling results with the existing institutional boundaries of

Greater Beirut. First, there is a strong correlation between the concentration and spread of the dense urbanized areas and the institutional allowable surface exploitation factor (SEF) of the zoning regulation. The trend does not go in a symmetrical centripetal way. As in the SEF, the northern stretch carries more density than the southern one (Fig. 8). Second, there is very little correlation between the metropolitan boundaries and the existing urban agglomeration with high and medium density membership. Whereas the northern boundary follows a natural geographic feature (Dog's River), the urban expansion reaches Jounieh northward and beyond.

5. Conclusions

This paper is a contribution to the making of urban models through the integration of both remote sensing and GIS technology that enable one to capture, manipulate, analyze, recognize patterns and display, all forms of geographically referenced information. These technologies were applied in the case study of the Greater Beirut area to help reveal in a global manner the geographically tied problem of identifying urban boundaries.

The above results represent a delimitation of the core urbanized areas of the Metropolitan Region of Beirut (MRB). This step will be complemented with a determination of the surrounding areas that exhibit a strong dependency on this core. The determination of the UB will then be based on the delimitation of the core areas, as well as identification of the dependent areas, and is the focus of ongoing research by the authors. Moreover, the fuzzy intensity of core urbanized area model will be validated based on travel-related statistics, the spread of the public and private bus networks over the territory, and the institutional structuring of the urban fabric through zoning regulations.

Finally, the findings of the research are opening further domains for investigation. Questions as to the validity of metropolitan boundaries, the challenges that should be addressed within their premises, and other parameters that should be taken into consideration are essential to our understanding of the dynamics of an urban environment that is in continuous flux and change.

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